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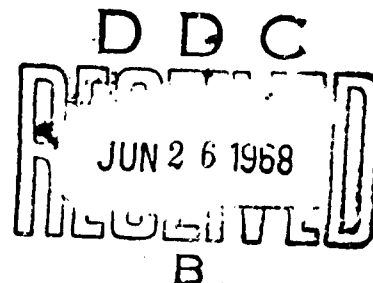
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TECHNICAL TRANSLATION 98

NEW DATA ON THE SENSITIVITY OF CONDENSED
EXPLOSIVES TO MECHANICAL SHOCK

N. A. Kholevo

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Feltman Research Laboratories
Picatinny Arsenal
Dover, New Jersey

NEW DATA ON THE SENSITIVITY OF CONDENSED
EXPLOSIVES TO MECHANICAL SHOCK*

(First Communication)

By N.A. Kholevo

Trudy Kazanskogo Khimiko-tehnologicheskogo In-
stitute imeni S.M. Kirova (Transactions of the
Kazan' Chemical-Engineering Institute imeni S.
M. Kirov), No. 10, 1946, pp. 91-105.

I. STATEMENT OF THE PROBLEM

1. The sensitivity of an explosive to mechanical effects is of interest primarily from the practical standpoint.

Many accidents and catastrophes accompanied by the loss of a considerable number of human lives and great material losses should be blamed on a poor concept of the phenomena caused by a mechanical effect on an explosive.

The study of the mechanism of the excitation of an explosion in the deformation of an explosive is also of great interest from the theoretical standpoint.

Incidentally, information concerning the sensitivity of explosives is limited chiefly to qualitative observations of phenomena and does not extend further to general hypotheses from the standpoint of the mechanism of these phenomena.

2. The sensitivity of an explosive is characterized by the probability of an explosion at a definite intensity of the mechanical effect and at definite conditions of this effect.

However, such a general concept of sensitivity is inadequate,

*Read at a conference at the KKhTI [Kazan' Chemical-Engineering Institute] (6 June 1946).

both from the practical and the theoretical standpoints.

3. In the study of sensitivity, the problem was stated, primarily, of that physical quantity which may be a measure of the sensitivity of an explosive to mechanical effects.

As a result of the analysis of data known from this standpoint, it was established that existing methods of characterizing sensitivity do not reflect the actual facts, and, consequently, may to a certain degree hamper a deepening of our understanding of the essence of the phenomena accompanying the process of the mechanical effects on an explosive.

4. In the process of experimental study of the phenomena observed in a shock on explosives, certain dependences were noted, which have served as the basis for new concepts of the sensitivity of explosives to mechanical effects.

II. DISCUSSION OF KNOWN METHODS OF CHARACTERIZING SENSITIVITY OF EXPLOSIVES TO MECHANICAL EFFECTS

1. General Remarks

5. The investigations of Lenze (8), Kast (9), Muraour (10), Wöhler and Martin (1), Taylor and Weale (2), Wöhler and Wenzelberg (3), Kondratskiy (5), Urbanski (4), and others have facilitated a considerable improvement in the technique of experimentation and a deepening of concepts of the phenomena occurring in a mechanical effect on an explosive.

6. According to existing concepts, the measure of the sensitivity of an explosive is the so-called mechanical initiating impulse.

A mechanical impulse is considered to be that quantity of mechanical energy that it is necessary to expend in order to cause the beginning of an explosive transformation (16).

However, the measure of sensitivity thus formulated turns out to be indefinite, because of the fact that in the expenditure of one and the same quantity of mechanical energy, the beginning of an explosive transformation may occur and may not occur, when independent repeated tests are carried out.

To eliminate the indefiniteness commented upon, we need a concept of the criterion of sensitivity.

The criterion of sensitivity is the probability of an explosion, which is determined on the basis of frequency, ascertained by experimental methods.

Thus, for the measure of sensitivity of an explosive we assume the mechanical impulse at a definite frequency of explosion.

Many test methods are known when some frequency or other is assumed as the criterion of sensitivity, and the mechanical impulse corresponding to this frequency is determined.

However, even such a method of characterizing sensitivity does not give the proper concept. The most highly perfected characteristic of sensitivity is considered to be the so-called sensitivity curve, which graphically expresses the functional dependence of the frequency upon the mechanical impulse. Such a sensitivity curve is ascertained by experimental methods under strictly standard conditions of the mechanical effect.

Without dwelling on a critical discussion of existing individual methods of characterizing sensitivity, we will shift to the problem of a mechanical impulse and of sensitivity curves.

7. A mechanical impulse is most frequently considered to be the energy of a shock, and it is expressed in $\text{kg}\cdot\text{m}$, i.e.,

$$U = PH \text{ kg}\cdot\text{m} \dots \dots (1)$$

With a constant weight of the load, in this case, usually only the height of drop of the weight is fixed.

Frequently an impulse, in accordance with proposition (1), is considered to be the energy of a shock per unit area of the distribution of the shock

$$U = \frac{PH \text{ kg}\cdot\text{m}}{S \text{ cm}^2} \dots \dots (2)$$

In individual cases, an impulse, according to proposal (3), is considered to be the difference between the shock energy (impact energy) and the recoil energy, per unit area of the distribution of the shock.

$$U = \frac{PH - PH_0 \text{ kg}\cdot\text{m}}{S \text{ cm}^2} \dots (3)$$

A proposal has been made (13) and (17) to accept the internal stresses arising in an explosive under impact as the measure of sensitivity.

However, this proposal, for reasons that are entirely understandable, has not found recognition.

8. The identification of an impulse of (1), (2) or (3)* is very convenient in that it may be measured directly very easily. However, this apparent advantage disappears in the consideration of such an impulse from the standpoint of its correspondence to reality.

Both (1) and (2), and (3), characterize only the intensity of the external effect on an explosive, and from this standpoint correspond to reality. But they cannot be a measure of sensitivity because of the fact that the quantitative expression of their magnitude, at a definite frequency (probability) of explosion, is not constant, but depends upon the conditions under which the external effect is accomplished.**

9. Only such a mechanical impulse whose quantitative expression remains constant under different conditions of the effect on the substance may serve as a measure of the sensitivity of an explosive to mechanical effects.

The magnitude of such an impulse depends only upon the nature of the explosive, the temperature, and the external pressure. In this case, the latter factor, for the condensed explosives under consideration by us, scarcely has any essential significance in the excitation of the explosion. This factor acquires significance only after the gaseous phase is formed, and the explosion phenomenon is already considered from the standpoint of the rate of its propagation.

10. It is apparent that the magnitude of the mechanical impulse depends directly only upon that mechanical energy that is "absorbed" by the explosives during the impact.*** No one has determined the quantity of this energy, and from this standpoint even tentative concepts are lacking. Besides, the energy absorbed is not uniformly distributed in the total volume of the explosive, as Taylor and Weale (2) and others assume, but is con-

*The dimensionality of the impulse in (2) and (3) is noted in the literature, without the corresponding stipulation with relationship to its conditional nature. Incidentally, with such a dimensionality, the case under consideration does not make any physical sense and, consequently, encounters a formal objection.

**This is similar to the case when for determination of the temperature in a boiler the quantity of heat liberated in the furnace is accepted as the unit of measurement.

***Different types of mechanical effects may exist: impact, friction, vibration, and others. Here we will consider a mechanical effect as accomplished in impact, the conditions of which, in principle, are shown in Fig. 1. However, the conclusions are also extended to other cases of such an effect.

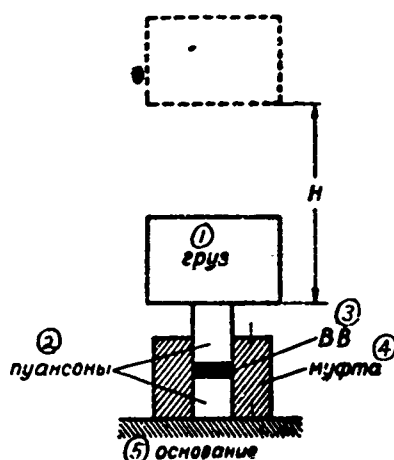


Fig. 1. Simplified diagram of the accomplishment of a shock under a hammer. 1) Weight; 2) Dies; 3) Explosive; 4) Coupling; 5) Base.

centrated in individual places to a greater or lesser degree. The magnitude of such concentrations of mechanical energy, as our tentative experiments show, is a determinant of the efficiency of the mechanical effect.

11. Thus, at the present time information is lacking concerning the mechanism of the shock (impact) phenomenon, and that mechanical impulse is not known by means of which we may measure the sensitivity of an explosive.

It is natural that under such conditions attempts to validate some theory or other of the mechanism of the excitation of an explosion do not have the necessary base.

As is well known, at the present time any generally accepted theory of the excitation of an explosion during a mechanical effect on an explosive is lacking. The so-called heat theory, advanced by Berthelot in his time, has been rejected by individual investigators (11, 12, 2). Other investigators (10) have tried to validate it by calculations, assuming impact energy as the mechanical impulse.

However, both attempts to refute the heat theory and attempts to validate it are deprived of the appropriate criterion by means of which the sensitivity of the mechanical impulse must be characterized.

12. In Section 6 it was noted that the most highly perfected characteristic of the sensitivity of an explosive is considered to be sensitivity curves, graphically expressing the functional dependence of the probability upon the impact energy. An example of such curves is found in the empirical sensitivity curves shown in Fig. 2, ascertained under test conditions corresponding to the simplified diagram represented in Fig. 1.

Primarily, from the standpoint of sensitivity curves we may make the following remarks. A sensitivity curve constructed for some explosive or other remains valid under strictly definite experimental conditions. But, even under standardized conditions, it is not always possible to reproduce the curve.

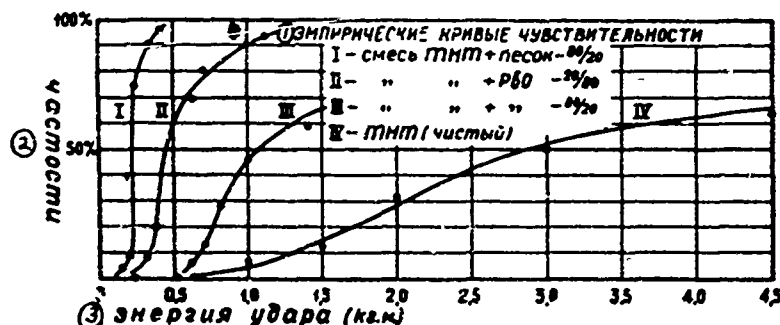


Fig. 2. 1) Empirical sensitivity curves: I - mixture of TNT + sand (80/20); II - mixture of TNT + PbO (20/80); III - mixture of TNT + PbO (80/20); IV - TNT (pure); 2) Probability; 3) Impact energy (kg·m).

Thus, the curve does not express sensitivity, as some definite property of the explosive. It only makes it possible to make a qualitative estimate of this property under strictly defined conditions of the mechanical effect.

This, generally speaking, may be adequate in individual practical cases, but is entirely inadequate for theoretical generalizations.

Experimental ascertainment of sensitivity curves has been accomplished by many authors. However, the sense of these curves for a long time remained incomprehensible, as a consequence of which they remained entirely uninvestigated. And only after Kondratskiy and Yakovlev (15) expressed the consideration that sensitivity curves are predetermined by purely random deviations, did it turn out to be possible to subject these curves to a theoretical investigation, using general methods of the theory of probabilities and mathematical statistics.

Interesting investigations of the sensitivity curves of detonating caps have been accomplished by Kondratskiy (5). The most interesting thing in the study of the sensitivity curves is their asymmetry. As the investigations of Miraour, Kondratskiy, and others show, sensitivity curves most frequently are asymmetrical (also see Fig. 2).

The affirmation of Taylor and Weale (2) that sensitivity curves, as predetermined by random deviations, must be symmetrical, as is apparent above, does not correspond to reality.

It is well known that the distributions predetermined by random deviations need not mandatorily be symmetrical, but may

also be asymmetrical. However, known methods of analytical expression of the function of asymmetrical distribution do not give us the opportunity to understand the "physical" essence of the phenomena being studied.

Kondratskiy in his work (5) writes: "Not one of the laws of asymmetrical distribution gives anything in common, except a mathematical description of the phenomena being observed."

Is it possible that we may extend the general principle noted above also to asymmetrical sensitivity curves? The asymmetry of these curves is predetermined only by random deviations. In what is expressed the physical essence and the cause of the asymmetrical distribution of the deviations predetermining the asymmetry of the sensitivity curves?

What factors chiefly affect the magnitude of random deviations predetermining the sensitivity curve, in general, and in what way? All these problems remain open, which to a certain degree makes the problem of the sensitivity of explosives more complicated.

2. General Conclusions

13. On the basis of the general remarks expressed above, we may make the following conclusions.

1. Impact energy is a measure of the intensity of mechanical effect, but cannot serve as a measure of sensitivity.
2. A measure of sensitivity may be determined only by that mechanical energy that actually, as it were, is expended directly, either via thermal energy or via some other type of energy, for excitation of the explosion.
3. Impact energy is a factor predetermining the excitation of an explosion. The efficiency of this factor depends strongly upon many other independent factors, determining the conditions of the mechanical effect on the explosive.
4. Impact energy may serve only as a certain relative qualitative characteristic of sensitivity under definite conditions of impact, providing for a constant (but unknown) efficiency.
5. The statement of the problem, in principle, of the nature and magnitude of the mechanical impulse, first of all, is of theoretical interest. The correct concept of the mechanical impulse may exclude fruitless theoretical generalization and erroneous practical conclusions, which frequently are made by guiding ourselves by the impact energy as a measure of the sensitivity of an explosive.

III. A NEW CONCEPT OF MECHANICAL IMPULSE

1. Nature and Magnitude of Mechanical Impulse

14. During a mechanical effect on an explosive; the latter is deformed. The work of the deformation (strain) is accomplished in a definite time and in a definite volume of the explosive.

Thus, the nature of the mechanical impulse (I) of interest to us is determined by the "intensity" of the mechanical energy and corresponds to the dimensionality (mechanical energy/volume, time). In this case, the magnitude of the impulse is not equal to the average value of the specific deformation power, but corresponds to the maximum power at individual places of the explosive being deformed. Taking this into consideration, the magnitude of the impulse is considered as a certain function of the quantity of energy absorbed during the impact, the volume of explosive being deformed, and the time of deformation.

$$U = \varphi(I, V, \tau) \dots \dots \dots (4)$$

15. The impact process consists of two periods. In the first period (characterized by an increase in the internal stresses in explosive) the main part of the work of deformation is absorbed and a lesser part is transformed into potential energy of elastic deformation of the explosive. In the second period (characterized by reductions in internal stresses) the potential energy of elastic deformation of the explosive, partially transformed to the work of deformation (in the reverse direction) is absorbed and, to a great part, is expended on an increase in the kinetic energy of the recoiling weight (see Fig. 1).

Ignoring the energy of the impact absorbed in the second period (as being very insignificant), by (1) we mean only that part of the energy that is absorbed in the first period of the impact.

The total quantity of mechanical energy (1) absorbed by the explosive may be determined by experimental methods.

For this purpose, preliminarily we determine the quantity of energy absorbed by the metal (weight, die, base, and other parts of the hammer) in cases of impact without explosives (see Fig. No. 1)

$$PH = I_1 + PH_1 \dots \dots \dots (5)$$

where I_1 is the quantity of energy absorbed by the metal; PH_1 is the recoil energy (H_1 is measured).

It has been established by special experiments that in

cases when the impact energy does not exceed a certain magnitude, the ratio of the energy absorbed by the metal to the height of recoil remains constant (with the same weight)

$$\frac{I_1}{H_1} = \frac{I_2}{H_2} = \text{const} \dots \dots \dots (6)$$

The energy absorbed by the explosives during the impact is equal to:

$$I = PH - I_2 - PH_2 \dots \dots \dots (7)$$

where I_2 is the energy absorbed by the metal; PH_2 is the recoil energy, due to the metal and the explosive. (H_2 is measured.)

We may select such a design of the appliance for explosives and so run the experiments that the recoil energy due to the explosives is practically equal to zero. Under such conditions, the equality of ratios (6) remains valid also in impact, when an explosive is located in the appliance, which makes it possible to find $I_2 = \frac{PH - PH_2}{H_1} H_2$ from (6). After substitution of

the value I_2 found into (7), the energy absorbed by the explosive is determined to be equal to

$$I = PH \left(1 - \frac{H_2}{H_1} \right) \dots \dots \dots (8)$$

16. For the purpose of experimental determination of (1), an appliance as represented in Fig. 3* was used. The results of certain experiments are presented in Table 1.

From a consideration of the table it is apparent that the energy absorbed by the substance increases more slowly than the impact energy, and in individual cases amounts to only a small part of it.

An even smaller quantity of energy is absorbed when the substance is placed in the appliance (see Fig. 1) upon condition that this substance is not squeezed out into the clearance between the dies and the coupling.

A detailed study of the problem of the magnitude of energy absorbed by various substances during impact is an object of our investigations.

17. If, as is apparent in Section 16, we may have a certain

*The application of such an appliance turned out to be feasible also in determining the probability of explosions, which induced us to replace the generally accepted appliance (schematically represented in Fig. 1) by it.

TABLE 1.

Absorption of Energy by Various Substances Under Impact

① № п/п	② Наименование вещества	③ Вес вещества в приборчике (г)	④ (PH) энергия удара (кг·м)	⑤ энергия погло- щаемая веществ- ном (кг·м)	⑥ Отношение 1:PH (%)
1.	Тротил	0,03	2,1	0,40	23
2.	"	"	1,0	0,40	40
3.	Парафин	0,05	2,1	0,12	6
4.	"	"	1,0	0,11	11
5.	Свинец	0,5	2,1	1,57	74
6.	"	"	1,5	1,22	76
7.	"	"	1,0	0,84	84

1) Sequence number; 2) Name of substance; 3) Weight of substance in appliance (grams); 4) (PH) impact energy (kg·m); 5) Energy absorbed by the substance (kg·m); 6) Ratio 1:PH (percent); 7) Trotyl; 8) Paraffin; 9) Lead; Note to Table 1. Actually, (1) is somewhat less than the magnitudes noted in the fifth column, which includes, besides (1), the kinetic energy of the substance forced out from under the die and the energy absorbed by the dies as the result of the friction of the substance against their surface.

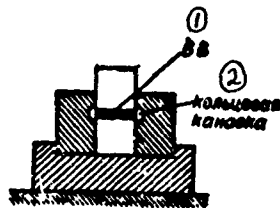


Fig. 3. Appliance of changed design. 1) Explosive; 2) Annular groove.

concept of the magnitude of the energy absorbed (1), the problem of the distribution of this energy and its maximum concentration in the elementary volumes of the explosive being deformed is considerably more complex.

Besides the nature of the explosive, the time of deformation has its effect on the magnitude of the maximum local concentrations of energy. The greater the deformation time is, the more uniformly the energy absorbed is distributed in the volume of explosive being deformed. Besides, both the magnitude of energy absorbed and its distribution depend upon the nature of the deformation of the explosive. The least quantity of energy is absorbed, and this energy is distributed most uniformly, during elastic deformation of an explosive. This predetermines very small local concentrations of energy and, as a consequence, a low magnitude

of the maximum impulse in individual places of the explosives being elastically deformed.

A characteristic example illustrating this circumstance is found in the results of experiments on the testing of the sensitivity of a mixture of trotyl with sand (40/60) in appliances 1 and 2 (represented, respectively, in Figs. 1 and 3).

During the impact, the mixture in appliance 1 was deformed chiefly elastically, and in appliance 2 frequently was squeezed out from under the die into the groove. As a result of such tests it was ascertained that to provide for a probability equal to 10 percent, in the first case, an impact energy of not less than 2.5 kg/m is required, while, in the second case, with an impact energy of only 1.0 kg/m the probability provided was equal to 100 percent.

We must remark that during the impact in the first case the maximum pressure on the explosive was greater than in the second case by a factor of 1.7.

This example also shows that in an impact the maximum stresses in the explosive are not a determining factor of sensitivity.

18. At the modern state of techniques of testing explosives on a hammer, for characteristics of the impulse, we must use an equation that is more general than (4). Impulse (I) may be represented as a certain function of a very large number of independent factors, determining the intensity and efficiency of the mechanical effect on the explosive.

$$U = \varphi(H, p, V, v, \dots) \frac{\text{energy}}{\text{volume, time}} \dots \dots \dots (9)$$

We may experimentally study the dependence of the impulse upon any of such factors, leaving the effect of all others as constant.

Thus, for example, an impulse may be represented as a function of the height of the falling weight.

$$U = f(H) \frac{\text{energy}}{\text{volume, time}} \dots \dots \dots (10)$$

This functional dependence is determined by the nature of the explosive, the weight of the falling load, the mechanical properties of the hammer, and other factors, predetermining the efficiency of the mechanical effect.

19. Since it is not possible to measure the magnitude of the impulse directly, in studying the functional dependence (10),

we must have some sort of criterion characterizing this quantity.

In the following section it is shown that such a criterion is the probability of explosion with repeated independent tests in a hammer.

2. Mechanical Impulse and Sensitivity Curves

20. Accepting the concept of the impulse as it was advanced, we may quantitatively express the sensitivity of an explosive as a certain definite magnitude of this impulse.

The phenomena of "explosion" or "misfire", in this case, depend only upon the magnitude of the impulse. If the sensitivity of a certain explosive is determined by the magnitude of the impulse (U_0), when the impulse is reduced by a very small magnitude (ΔU), a misfire is obtained; and when it is increased by a very small magnitude, an "explosion".

We will assume that the intensity and efficiency of a mechanical effect on an explosive vary so that with each independent subsequent effect, the impulse is increased by a very small magnitude. It is apparent, in this case, that at first misfires would be observed; and then, with a certain following effect, when the impulse has reached a critical magnitude (U_0), an explosion would occur. The explosion would be repeated also in successive effects providing for a larger impulse. The magnitude of the impulse (U_0) thus found is a measure of the sensitivity of the explosive to mechanical effects.

However, such a method of determining sensitivity may be only theoretical. In a practical study of sensitivity, the problem turns out to be considerably more complex.

21. Let us assume that the independent mechanical effects on an explosive are reproduced, with observation of all conditions of the effects as the same.

We will assume that such repeated tests are accomplished in a hammer with a certain height (H_1) of the falling weight. In this case, each repeated test is accompanied by the measurement of the magnitude of the impulse. Having plotted on the abscissa axis the quantity (H_1), and noting the ordinates corresponding to the magnitude of the impulses at each repeated test, a certain vertical row of points is obtained (see Fig. 4). The distribution and magnitude of the deviations of the extreme points are predetermined by random deviations in repeated tests of a very large number of factors affecting the impulse.

Having changed the height of drop of the weight and having left all the other factors unchanged, we may find the same type

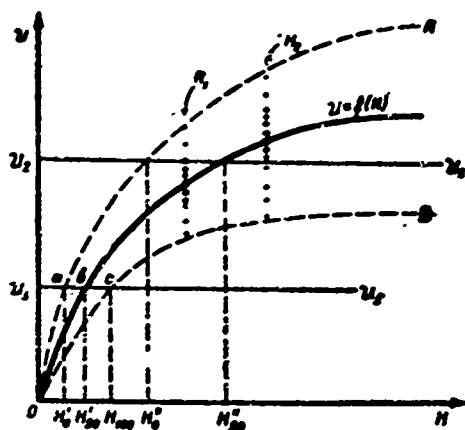


Fig. 4.

of vertical row of points (see Fig. 4) corresponding to the new height (H_2).

By accomplishing the same thing also at other heights of drop of the weight, we may fill in a certain area with points.

In Fig. 4 this area is marked by the dashed lines OA and OB.

Having connected the point corresponding to the medians by a continuous line, a certain line is obtained (see Fig. 4) expressing the functional dependence of the impulse upon the height of the dropping weight (upon the impact energy)

$$U = f(H) \dots \dots \dots (11)$$

Since the deviations in the magnitude of the impulse (scattering of the points in each row) are predetermined by random deviations of a very large number of quantities affecting the impulse, we may think that the scattering of the points in each row is symmetrical relative to a point of the corresponding median. In this case (11), we find the same thing as in (10).*

22. Let us imagine that an impulse providing an explosion of the explosive being studied is equal to a certain magnitude (U_1). By drawing a horizontal line corresponding to this impulse (see Fig. 4), we may mark the points of intersection "a", "b", and "c".

Point "a" corresponds to a certain maximum height (H_0) at which the probability of an explosion is close to zero. Point "b" corresponds to a certain height (H_{50}), at which the probability of explosion is equal to 50 percent, since above this point we find 50 percent of the points corresponding to impulses greater than (U_1).

On the basis of the same consideration, we may note that point "c" corresponds to a certain height (H_{100}) at which the probability of explosions is 100 percent. All heights between (H_0) and (H_{100}) corresponding to points of the segments (ac) correspond to definite probabilities of from 0 percent to 100

*The essence of the following discussion does not change, even if the scattering of the points in the row is symmetrical and (11) is different from (10).

percent.

Similar arguments may also be given if the impulse exciting the explosion of the explosive being investigated is equal to (U_2), etc.

23. It is not difficult to see that the dependence of the probability upon height (H) noted in Section 22 is a sensitivity curve. By using Fig. 4, such sensitivity curves for explosives corresponding to impulses (U_1) or (U_2), or to any other impulse, may be graphically constructed. For this, on the abscissa axis we plot the heights and on the ordinate we assume the appropriate segments between the line corresponding to the impulse (such as, for example, U_1 or U_2) and the line OA .

24. Thus, if we know (U_1), $f(H)$, and the extreme deviations of the magnitude of the impulse, we may construct a sensitivity curve for the explosive without performing the corresponding tests. The natural thought arises of solving the inverse problem:

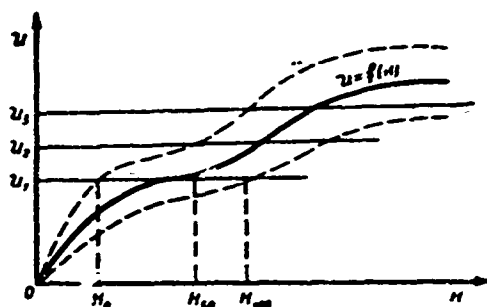


Fig. 5.

on the basis of sensitivity curves (ascertained under various conditions of mechanical effects) for a definite explosive, find the magnitude of the impulse exciting the explosion of this explosive. It is true that the quantitative value of the impulse cannot be found by such a means, but, apparently, we may find the quantitative ratio of the impulses for various explosives; this also is of practical and theoretical interest. However, the solution of such a problem, apparently, requires a quite complex mathematical processing of the results of the experimentation.

25. In the consideration of Fig. 4 it is apparent that the asymmetry of the sensitivity curves depends upon the form of $f(H)$ and the magnitude of the extreme deviations of the impulse. In this case, if we admit that $f(H)$ actually has a form similar to that represented in Fig. 4, it becomes understandable why the empirical sensitivity curves (see Fig. 2 and Section 12) for less sensitive explosives differ in having greater asymmetry than for more sensitive explosives, and why for trotyl we still have not succeeded in constructing a complete sensitivity curve (see line U_2 and line OB in Fig. 4). From Fig. 4 we also may note that the upper branches of the sensitivity curves are longer than

the lower branches, which is also actually observed.*

26. The values of $f(H)$ represented in Fig. 4 show that as (H) increases the impulse (U) increases more slowly.

The results of the experiments given in Table 1 may also serve as a confirmation of such a quantitative relationship.

As is apparent from the table (compare experiments 1 and 2; 3 and 4), the quantity of energy absorbed (i) does not change proportionally to the impact energy, but considerably more slowly. Since the magnitude of the impulse is a direct function of the energy absorbed (i) , we may think that the dependence of (i) noted upon the impact energy remains valid also for the impulse.

3. Mechanical Impulse and Probability of Explosions

27. The circumstance that in repeated tests in a hammer (in spite of the most careful observations of the same conditions) either an explosion or a misfire may occur, forces us to think about those reasons that predetermine this phenomenon. Unfortunately, at the present time experimental data are known chiefly from the standpoint of the dependence of the probability of explosions upon impact energy. Incidentally, a more detailed ascertainment of the dependence of the probability upon other facts having an influence upon it is of interest.

It is not doubted that some probability of explosions or other is predetermined by random deviations. However, we may think that the effect of individual causes predetermining random deviations is not always the same. Apparently, in repeated tests it is primarily the effect of only certain of them that occurs.

It is difficult to admit that random deviations in impact energy, weight of explosives, temperature, sizes of crystals, quantity of additives, and properties of appliances may be determining. In certain cases, we may change all these quantities simultaneously and deliberately (even somewhat more than possible random deviations) toward facilitating an explosion or a misfire. And nevertheless, in this case, neither 100 percent or 0 percent probability will be provided.

28. With the present views on impact energy as a measure of sensitivity it is difficult, for example, to explain the quantitative relationship of the variations in probabilities

*Theoretically we may admit a case of an inverse ratio of the branches of the sensitivity curve (see Fig. 5). However, such cases are not known to the author for empirical sensitivity curves.

as represented by curve IV (see Fig. 2). If in an impact energy (see Fig. 2) equal to 1.0 kg/m explosions are already provided and misfires may be considered as due to random deviations in a direction unfavorable for an explosion, then, it would appear that with an increase in the impact energy by a comparatively small magnitude we may "compensate" for all unfavorable random deviations and achieve 100 percent explosions.

Incidentally, experience demonstrates that when the impact energy is increased even by a factor of 4.5, nevertheless we do not succeed in achieving 100 percent explosions. Moreover, in general we do not succeed in achieving 100 percent explosions for trotyl at all.

Already only this observation may excite the thought that some probability of explosions or other is a consequence of more complex causes than random deviations of the "external" conditions of the mechanical effect.

29. The new concept of mechanical impulse gives us the opportunity to consider the scattering (deviation) of the magnitude of the impulse instead of the probability of explosions. In Section 22 it was demonstrated that, considering the scattering of the magnitude of the impulse (see Fig. 4), we may explain the reason for the asymmetry in the sensitivity curves and the dependence of the asymmetry upon the sensitivity of the explosive.

We may also, in ascertaining the reasons causing some probability or other, consider the causes predetermining the scattering of the magnitude of the impulse. It is apparent that these reasons are one and the same.

30. In the excitation of an explosion, we may consider two problems. The first is the problem of increasing the rate of the chemical reaction to some critical magnitude (initiating an explosion). The second is the problem of the involuntary propagation of this reaction in the mass of the explosive (development of the explosion).

The intensity of mechanical energy (or, which is the same thing, the magnitude of the impulse under consideration), determines the rate of the chemical reaction. Involuntary propagation of the reaction depends upon a great number of other causes.

31. The results of tentative experiments available at the present time indicates that in a mechanical impact at first a chemical change of the substance occurs, and an explosion can occur only after this. As a result of these same experiments it was ascertained that the chemical change of the substance occurs

in individual places (in a greater or lesser number). The involuntary propagation of the reaction begins from these places (seats). However, to guarantee an explosion of all the weighted portions or part of it, it is necessary that there be many such "seats." Otherwise the reaction may cease.

32. In view of the fact that we have set ourselves the purpose of considering the reasons for the scattering of the magnitude of the impulse, it is necessary, in the determination of the probability of explosions, to take into consideration the phenomenon of the "origin of the explosion", without giving ourselves the task of studying the problem of the "development".

Consequently, in repeated shocks by explosions, all cases are considered when a noticeable change of the explosive is observed (darkening, charring, smoke, burning out, sound, etc.).

33. Considering everything expounded above, we may, with relationship to probability of explosions, express the following considerations.

In a mechanical effect, in individual places of the explosive being deformed, impulses arise, whose magnitude is not uniform. In the reproduction of such a mechanical effect secondarily, the distribution of impulses and the maximum magnitude of individual effects from among them will be different than in the first effect, and this phenomenon is predetermined by random deviations. We cannot thus accomplish the repeated effect in order to provide one and the same magnitude of maximum "elementary" impulses and exactly the same distribution of them in the volume of the explosive.

The circumstance noted is predetermined by the fact that in certain repeated tests, in individual places impulses originate providing for a critical rate of the chemical reaction in these places; in other tests, this may not occur.

34. The phenomenon described in Section 33, when the external conditions are changed, such as, for example, when the impact energy is increased, is correct in that what is changed is characterized by the change in the extreme deviations of the maximum values of the "elementary" impulses. The nature of such a change in Fig. 4 is shown conventionally by dashed lines.

35. The picture of random phenomena represented should be considered as a rough, simplified scheme of those phenomena which actually occur.

The refinement of this scheme may be accomplished after the appropriate experimental and theoretical investigations.

36. Some confirmation of the reality of everything expounded above may be seen in an analogous phenomenon in dynamic tests of metals.

As is well known (18), in repeated dynamic tests of the mechanical strength of metals, a random distribution of the test results is observed, characterizing a definite probability; this is similar to what occurs also in mechanical effects on explosives.

Both in the testing of metals and in the testing of explosives, a common factor is the fact that in both cases a deformation (strain) of the substance is accomplished in a short period of time.

The nature of the random deviations both in the first and in the second case, apparently, are one and the same.

IV. PHENOMENA DURING IMPACT IN A HAMMER

37. As was already mentioned above, the origin of an explosion begins in individual places in the explosive. In those cases when the explosive is under pressure and during an impact flows out into the clearance between the dies and the matrix, the origin of an explosion frequently begins in the clearance (appliance 1).

It is very convenient to observe places (centers) of origin of an explosion, when the explosive is mixed with a large quantity of very fine silica or glass (size of particles about 0.01 mm). In this case the propagation of the explosion is hampered, and the places where decomposition begins may be easily detected by means of a magnifying glass or under a microscope. Experiments have shown that the volume in which decomposition in such a mixture is observed increases when the impact energy is increased. This is explained by the fact that as the impact energy increases, the number of centers of origin of the explosion also increases.

The centers of origin of the explosion unavoidably originate closer to the surrounding limiting area of the dies, which is a consequence of the uneven pressure of the latter during the impact.

38. The study of the behavior of mixtures of various explosives with silica has shown that with one and the same quantity of impact energy being absorbed, the probability of the origin of centers of decomposition depends strongly upon the size of the particles of silica.

The finer the particles of the latter are, the lower is the sensitivity of the mixture. Such a dependence, observed from experiments, is entirely understandable, if we take into consideration the fact that as the size of the particles decreases and their number increases, the energy absorbed is more uniformly distributed in the total volume and its maximum concentration in the elementary volumes is less.

39. On the basis of general observations it has been noted that, depending upon the impact energy, the "degree" of decomposition of the explosives may differ. It is especially convenient to observe the dependence noted when testing a mixture of explosive with silicon in appliance No. 2. In this case, the quantity of changed explosives forced out during the impact may be removed from the groove (in the coupling) and inspected.

Experiments with trotyl, tetryl, and other explosives have demonstrated that the latter may be changed without liberating a noticeable quantity of "gaseous products," which is discovered by the absence of odor, smoke, or sound.

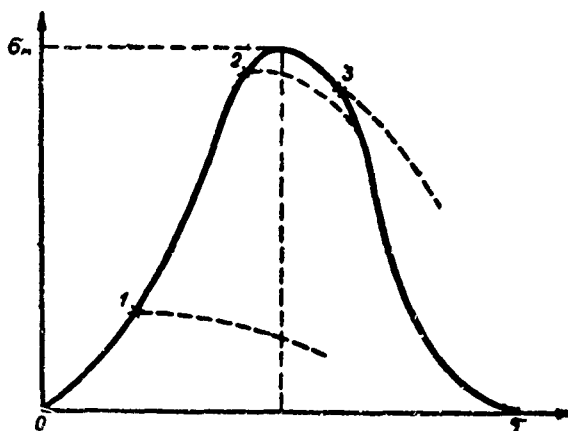


Fig. 6. Simplified diagram of the change in stresses in an explosive during impact under a hammer.

Interesting phenomena could be observed in the testing of hexogen in the presence of 5 percent silica. As a general rule, in the explosion of hexogen no soot is observed. However, at very weak impact, the mixture mentioned decomposed with the formation of a black deposit (carbon black?) on individual parts of the appliance.

40. During an impact an explosion may occur, arguing theoretically, at various moments of time of the impact. In Fig. 6 we show a simplified diagram illustrating the dependence of

stresses (δ) and time upon the beginning of impact (τ). In cases when there is no explosion, the dependence is expressed by the solid line. In this case, the magnitude of maximum stresses (δ) is characterized by the height of recoil of the weight after the impact. Theoretically possible cases of explosion are marked in Fig. 6 by figure 1, 2, and 3.

Experiments with hexogen (without silica) showed that actually, the theoretically expected cases occur. With a considerable height of the falling weight, explosions occur (most frequently) at the first moment (marked in Fig. 6 by the figure 1), when the weight still has a significant kinetic energy and stresses in the metal (and in the explosive) are small.

With a lower height of the falling weight explosions (most frequently) occur at the second or at the third moment, when the kinetic energy of the falling weight is very small, or when the weight is already moving in the reverse direction (recoiling) and the stresses in the metal are significant.

The dependence noted of cases of explosion upon the height of the falling weight is statistical.

It is possible to control and judge the moment of explosion in experimentation by noting the height of the recoiling weight after the impact. In those cases when the explosion occurs at the first moment, the recoil of the weight is small. This is explained by the fact that a great part of the impact energy, in this case, is absorbed by the gases formed during the explosion. The gases in this case are very good shock absorbers for the impact; as a consequence of which the stresses in the metal remain small and, as a result, a small recoil of the weight occurs.

In those cases when the explosion occurs at the second moment, the kinetic energy of the weight is already small, and the stresses in the metal are significant. The recoil of the weight in this case naturally should be greater. An even greater recoil must occur in cases of an explosion at the third moment.

Experiments have shown that in cases of an explosion at the second moment (or at the third), the height of recoil may even be greater than the height of fall of the weight.

Thus, cases are observed when a recoiling weight strikes against the lowering attachment and automatically couples to it (the design of the lowering attachment permits this phenomenon). Explosions at the second or the third moments were accompanied by a louder noise and a greater scattering of the in-

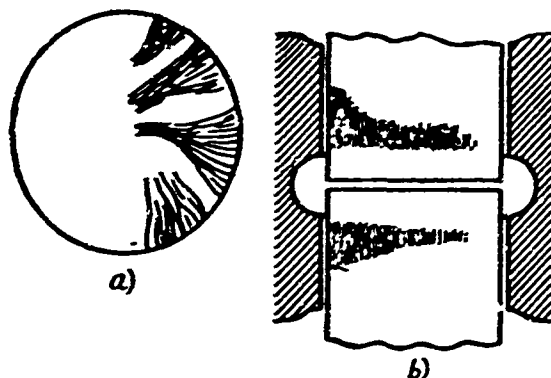


Fig. 7. Diagram of the effect of products of explosion on the surface of dies.

dividual parts of the appliance.*

Thus, the experiments demonstrated that an explosion may occur at a greater or lesser pressure on the dies, and consequently the pressure on the explosive is not a determining factor, as was already noted in Section 17.

41. The dependence of the height of recoil of the load upon the moment of explosion noted in Section 40 was accompanied by a definite state of the surface of the dies after the explosion. In this case it was noted that in those cases when the recoil of the weight was small (explosion at first moment), a blue "tempering color" was always present on the surface of the dies (see Fig. 7, a). This phenomenon shows that during an impact, strongly heated products of explosion are forced out from under the dies. From the nature of the pattern of the blue spots (with a greater or lesser tint of yellowness), we could judge the direction of motion of the hot products, and their distribution under the die, etc.

In Fig. 7, a, we represent a typical example of the distribution of tempering color on the surface of the dies. As a result of the observation of the tempering color for a very great number of cases of explosions, the conclusion was made that the origin of the explosion begins at individual places (points). Such places are seats from which the explosion is propagated in the explosive. Since such a distribution of the explosion is accompanied by the forcing of explosive (at a great velocity) from under the dies, on the surface of the latter the

*In cases of the mixture of hexogen with even a small quantity of silica, explosions always occurred at the first moment.

hot gases leave a trail (tempering color) in the form of the trail of a comet. The number of such "trails" and their distribution throughout the surface depend upon the number and distribution of the seats of excitation of the explosion.

In those cases when during the explosion the recoil of the weight was great (explosion at second or third moment), patches of blue or some other color were always absent from the surfaces of the dies considered (Fig. 7, a).

In these cases, the tempering color (blue) could be observed only on the lateral surfaces of the dies (see Fig. 7, b) similar to what occurred also in cases of explosion at the first moment.

The absence of spots on the surfaces of the dies in contact with the explosives show that in this case the hot products of explosion are not forced out from under the dies.

Since excitation of an explosive decomposition may be expected only during the deformation of the explosive under the dies, the thought arises that in the case under consideration the development of an explosion with the formation of hot decomposition products outside the dies is predetermined by some delay of the explosion in time (after its excitation).

Thus, to explain the phenomena observed, we must assume that after the excitation of the explosion, before the formation of products with a high temperature, some short interval of time passes.

A more detailed study of this interesting phenomenon, we may think, will give us guiding presumptions for ascertaining the mechanism of the explosion during its mechanical excitation.

42. It is interesting to note that an explosion of hexogen is always preceded by a change in its physical state. This phenomenon may be especially clearly observed in repeated tests in appliance No. 1. In those cases when there is no explosion, the hexogen remains in the appliance after the impact in the form of a highly compacted cake between the dies; in this case, no sort of changes (fusing of crystals, darkening, or others) were observed. In cases of an explosion, the hexogen was first (explosion at second or third moment) forced out into the clearance between the dies and the coupling, where it exploded. Such a forcing of the substance into the clearance may occur only after the transformation of the hexogen into a liquid state (or at least to some other state than a solid state).

As the result of the transformation into a liquid state,

after the explosion a thin film of liquid matter always remains on the surfaces of the dies (see Fig. 7, a), which after a short interval of time crystallizes. The film of liquid matter remains not only in cases of an explosion at the second or third moment, but also in cases of an explosion at the first moment. In the latter case, the film covers only those sections of the surface which remain unoxidized.

The presence of a film of matter after an explosion on the surface of the dies also illustrates the fact that the development of the explosion in a thin layer between metallic surfaces does not occur.

Our continuing investigations on the study of the phenomena noted will make it possible to dwell in more detail on the problems of the mechanism and their causes.

SUMMARY

As a result of a critical discussion of known methods of characterizing the sensitivity of explosives to a mechanical shock, the conclusion is made that the impact energy cannot serve as a measure of sensitivity. The concept of impact energy as a measure of sensitivity excludes the possibility of explaining the physical essence of asymmetrical sensitivity curves and facilitates erroneous conclusions from the standpoint of the mechanism of the excitation of an explosion.

We advanced a new concept of mechanical impulse, which may be a quantitative measure of the sensitivity of an explosive. The dimensionality of such an impulse corresponds to the dimensionality of the specific deformation power and is characterized by the "intensity" of the mechanical energy absorbed in individual places in the explosive being deformed (the rate of absorption of mechanical energy).

On the basis of the new concept of the nature of the impulse and the results of tentative experiments, certain phenomena in mechanical effects on an explosive are explained. The main reason predetermining the scattering of the results during repeated experiments is noted. The causes of asymmetrical distributions of the probabilities, in the change of the impact energy, are explained, and the trend in the investigation for ascertaining the quantitative ratio of the sensitivity of explosives is noted.

A method has been developed for quantitative determination of the energy absorbed by an explosive during impact.

It has been experimentally ascertained that the energy ab-

sorbed in individual cases is considerably lower than the impact energy. In this case, as the impact energy increases, the energy absorbed increases considerably more slowly.

Phenomena are noted during an impact that characterize the moment of explosion, the stresses in the explosive before the explosion, delay time of the explosion, and others.

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